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Design and Field Test of a Galvanometer Deflected Streak Camera

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ABSTRACT

We have developed a compact fieldable optically-deflected streak camera first reported[1] in the 20-th HSPP Congress. Using a triggerable galvanometer that scans the optical signal, the imaging and streaking function is an all-optical process without incurring any photon-electron-photon conversion or photoelectronic deflection. As such, the achievable imaging quality is limited mainly only by optical design, rather than by multiple conversions of signal carrier and high voltage electron-optics effect. All core elements of the camera are packaged into a 12"x24" footprint box, a size similar to that of a conventional electronic streak camera. At LLNL's Site-300 Test Site, we have conducted a Fabry-Perot interferometer measurement of fast object velocity using this all-optical camera side-by-side with an intensified electronic streak camera. These two cameras are configured as two independent instruments for recording synchronously each branch of the 50/50 splits from one incoming signal. Given the same signal characteristics, the test result has undisputedly demonstrated superior imaging performance for the all-optical streak camera. It produces higher signal sensitivity, wider linear dynamic range, better spatial contrast, finer temporal resolution, and larger data capacity as compared with that of the electronic counterpart. The camera had also demonstrated its structural robustness and functional consistence to be well compatible with field environment. This paper presents the camera design and the test results in both pictorial records and post-process graphic summaries.

Keywords: streak camera, optomechanical streak camera, nanosecond streak camera, charge couple device, galvanometer scanner

1. INTRODUCTION

For many decades, there are basically two categories of time resolving instruments, the electronic and the rotating mirror streak cameras. The electronic streak camera serves brilliantly in its time resolving ability but with limited sensitivity and spatial resolution. The mechanical rotating streak camera provides high spatial resolution but has limited speed and its useful timing window can not be randomly accessed or externally triggered. A triggerable mirror deflecting mechanism such as using a galvanometer or piezoelectric deflector shall fill the gap between those two categories. As reported[1] in the 20th ICHSPP, the speed limitation can be substantially alleviated by implementing multiple reflections from the deflector. Modern scientific-grade imagers of CCD or CMOS sensor can be adopted as film replacement for direct large-format imaging with high sensitivity and resolution at reasonable cost. A desktop or laptop computer can be used for instant digital image capture and processing without any data degradation. The galvanometer streak camera is such a new instrument leveraging those attractive technology features. This paper is a progress report on our continuing effort to further advance the performance and functionality of the galvanometer deflected streak camera.

2. OVERVIEW OF ALL-OPTICAL DEFLECTED STREAK CAMERA

The traditional electronic deflected streak camera has tremendous speed capability for temporal resolution in the range of sub-nanosecond and below. It thus has been and shall continue to be the vital and only streak camera mechanism for resolving ultra-fast temporal scale. However, its basic mechanism involves multiple stages of signal carrier conversions between photon and electron with limited conversion efficiency. These conversions, occurring at photocathode and phosphor screen of both streak and intensifier tubes, limit the camera sensitivity and imaging fidelity. Proximity imaging relay and coupling of fiber optics faceplates further compromise the camera spatial resolution. In contrast, a tubeless streak camera[1] based on mirror deflection retains optical signal strength and quality throughout the streak recording process in a single carrier conversion at the CCD sensor. Relatively slow speed is the limitation of a triggerable mirror deflector such as a galvanometer. Note that the exception being a gas-turbine driven rotating mirror camera which is capable of high speed but can not be readily triggered as a slave unit with certain timing prediction accuracy. Figure 1

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illustrates the basic deflection frameworks of both electronic and all-optical deflected streak cameras. Table 1 lists summary of functional characteristics for these two types of streak cameras. The mirror speed limitation can be substantially mitigated by leveraging the mirror's optical characteristics of allowing easy repeated reflections, unlike the disallowing of electronic beam reflection. Figure 2 illustrates the optical arrangement of employing a retroreflective wedge-gap shape deflector[1] to provide a multifold increase in effective optical deflection speed. In this scheme, N reflections from the moving mirror would yield for the output beam an angular speed equal to 2N times mirror's rotating speed. The lens serves both for collimating the incoming fixed beam and for focusing the outgoing deflecting beam. The beam transverse between the two wedge-gap mirrors is collimated in the direction perpendicular to the slit length.

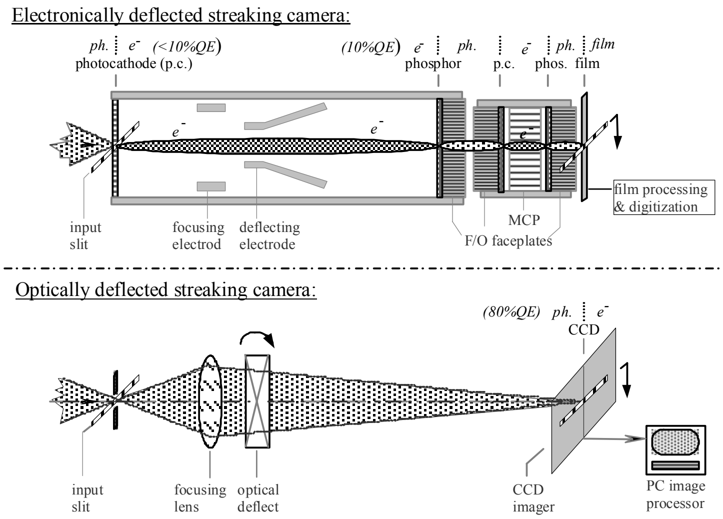

Figure 1. Basis frameworks of electronic and all-optical deflected streak cameras. In the all-optical camera, only one signal carrier conversion exists at the CCD imager with high QE.

Table 1. Summary of key functional characteristics

Electronic streak camera
• Time resolution < 1-ns • Trigger jitter < 1-ns • Trigger delay < 1-ns
• Multi-step signal conversion at low efficiency • Diverging re-emission degrades spatial resolution • Proximity-coupled film or CCD recording • Limited range of adjustable streak speed • Streak speed accuracy subject to circuitry ringing • Vacuum tube at high voltage
Galvanometer streak camera
• Time resolution > 30-ns • Trigger jitter > 25-ns • Trigger delay > 2-ms for speed ramp-up
• Single step signal conversion @ ≤80% QE • Diffraction limited imaging retains image fidelity • Direct lens-coupled recording with cooled CCD • Wider range of adjustable streak speed • Moment-of-inertia scanning at speed constancy • Solid state device at low voltage

3. DESIGN OF A GALVANOMETER DEFLECTED STREAK CAMERA

A galvanometer suits well as the mirror deflection owing to its high torque driving power, precision movement, repeatable timing response, nominal cost at about $5k, and ability to be triggered from a master timing control instrument. We have consistently observed a trigger jitter of as short as ±25ns if the interval between successive triggers is less than 10 second. The amount of jitter increases with the interval due to the sensitivity of galvanometer's driving circuitry to ambient and component temperature. Here the jitter is defined as the time variation from triggering of scan rotation initiation to arriving at a desired positional target. Being a mechanical device, a galvanometer takes certain time to ramp-up to an optimized constant rotational speed for performing linear optical deflection across the sensor area. This trigger delay of arriving at a desired streak starting position is nominally about 2 ms or longer depending upon mirror's inertia, targeted deflection speed, and driving voltage waveform input to the galvanometer.

The compact fieldable camera we have developed is composed of the galvanometer scanner as deflection driver, a retroreflective wedge mirror pair as the deflection speed multiplier, and a CCD as the direct-write imager. Core elements of the camera including scanner, optical components, slit, and CCD imager head are packaged into a 12"x24" footprint box, a size similar to that of a conventional electronic streak camera. Figure 3 illustrates the component arrangement inside the box. A desk top computer controls the camera and acquires the streak image in 16-bit per pixel accuracy for immediate display and processing. Specifically, the galvanometer is a moving-coil scanner Model 6650 with high stability servo amplifier Model 6025AHM by Cambridge Technology, Inc. of Watertown, MA. A synthesized function generator, Model DS345 of SRS Inc., Sunnyvale, CA, provides easy programmable waveform to drive the galvanometer. The scanning quartz mirror, made in-house at LLNL, is 20x70 mm^2 in size with ≥99% reflectivity at 532 nm and ≤λ/4 flatness. The collimating and focusing lens is a high quality achromat of 80mm diameter aperture and 310mm focus length. The slit dimension is 100μm width by 24mm long. Each of the two fibers transmitting fiducial timing pulse train is placed near each end of the slit opening. Three high reflectivity mirrors are used for beam path folding and turning.

The CCD is a scientific grade backside illuminated 1kx1k-pixel imager having nearly 75% QE at 532nm. The imager is thermoelectrically cooled down to about -45^{o} Celsius with circulating water for heat removal. It is a standard model by Roper Scientific, Inc. of Trenton, NJ. The computer platform can be either PC or PowerMac. Most of the opto-mechanical components and electronic instruments required for the camera are off-the-shelf items with the exception of the scanning mirror and the slit. The compact camera box is robustly constructed. The entire camera system is well suited for fielding application with consistent functionality and performance.

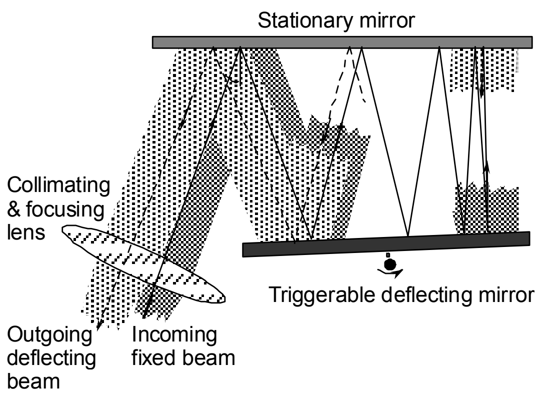

Figure 2. This wedge-gap shape retroreflector provides multifold increase in effective deflection speed

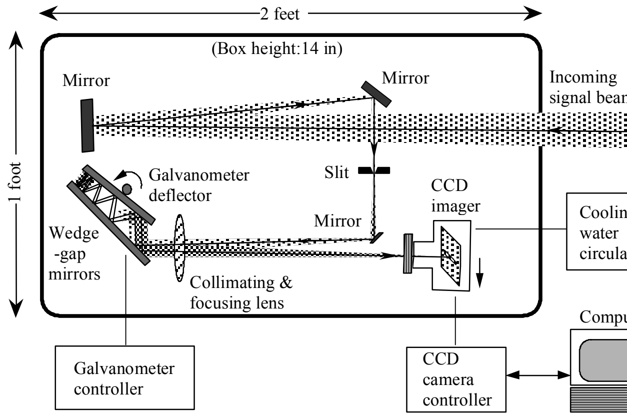

Figure 3. Schematic arrangement of the galvanometer deflected streak camera. Most of the components are off-the-shelf items.

4. FIELD TEST RESULTS OF BOTH TYPES OF STREAK CAMERAS

An experiment test measurement was performed at LLNL Site-300's Manybeam Velocimeter[2] facility using both galvanometer and electronic streak cameras recording the same signal of equal strength through two channels of the 5-beam velocimeter. A signal produced by the flat plate movement experiment was split 50/50 and fed into one of the two channels. Each split beam passes through the only Fabry Perot etalon of the velocimeter, but is recorded simultaneously by each of the two cameras. The test setup is designed to produce the same performance characteristics if same type of cameras were used to record both beams.

The electronic streak camera incorporates an image intensifier with gain set at rather high level as determinate by pre-event dry runs for optimal recording. Its streak speed is set on the camera dial at 30μs for roughly covering the streak tube's active phosphor screen but registers only 22μs over intensifier's 40mm diameter. The streak image is recorded on Kodak's T-MAX 3200 professional film. A reference wedge stripe of linear intensity variation is pre-exposed near the edge of same piece of film for post-development intensity calibration purposes. For obtaining the film image data reported here, the developed film is digitized by a drum scanner into 16-bit intensity depth. A scaling curve for exposure adjustment in Photoshop image processing program is generated by trial-and-error fitting until a nearly linear intensity variation is optimized for the reference wedge data. The curve thus obtained is then applied by Photoshop to the entire streak image to produce an approximately linearized digital image for subsequent quantitative evaluation. In contrast, the CCD image acquired by the galvanometer camera does not need any processing except for flat ADC background count subtraction. The digital image data are immediately ready for quantitative analyses.

The Fabry-Perot etalon contains two cavities. Each cavity produces a set of fringe patterns, named here as the primary and the secondary set. A streak image records the time resolving trace of both fringe sets as the Doppler-shifted signal reflecting and tracking the movement of the flat plate test object. Velocity change of the movement thus results in the fringe trace change along the spatial direction. Each set of fringes consists of several orders of symmetrical fringe pairs spreading from the central line toward the upper and lower half of the image. There are five order pairs for the primary set in the test result images. When the test object starts to move rapidly from stationary state, a jump-off of fringe patterns appears. The jump-off occurs at near the 1/3 mark of the record length for both cameras. Two trains of fiducial timing marks are also recorded at the upper and lower edge of the images. Timing mark is generated at every 500ns interval except for the intentional blocking of 1, 2, or 3 marks in a group serving as absolute timing registration. In the following, test results acquired by both cameras are presented side-by-side under specific performance parameter.

4.1. Images of Streak Record

Figure 4 is the image acquired by the galvanometer streak camera. Figure 5 is the digital intensity-linearized film image recorded by the electronic streak camera. Desired features to look for in these records are visible appearance of all primary and secondary fringe sets, fringe trace clearance, timing mark sharpness, and the total data content in one image. The four arrows with designated fringe labels between Figure 4 and 5 link the corresponding fringes for the images. The fiducial timing is the same at 500ns interval for both images. The total record length is 32μs for galvanometer camera and 22μs for the electronic one. Furthermore, the pixel intensity counts in Figure 4 occupy only a very small portion of the CCD's full-well capacity for each pixel, the maximum signal of <300 counts versus pixel saturation of 16 bits at 65536 counts. We have measured[1] the linear response dynamic range ratio of the galvanometer camera being better than 10000-to-1. Clearly, the galvanometer camera result in Figure 4 has profoundly demonstrated higher signal sensitivity in capturing more fringes with better image clarity, sharper timing marks, wider dynamic range, and contains more data than that shown in Figure5 by the electronic streak camera.

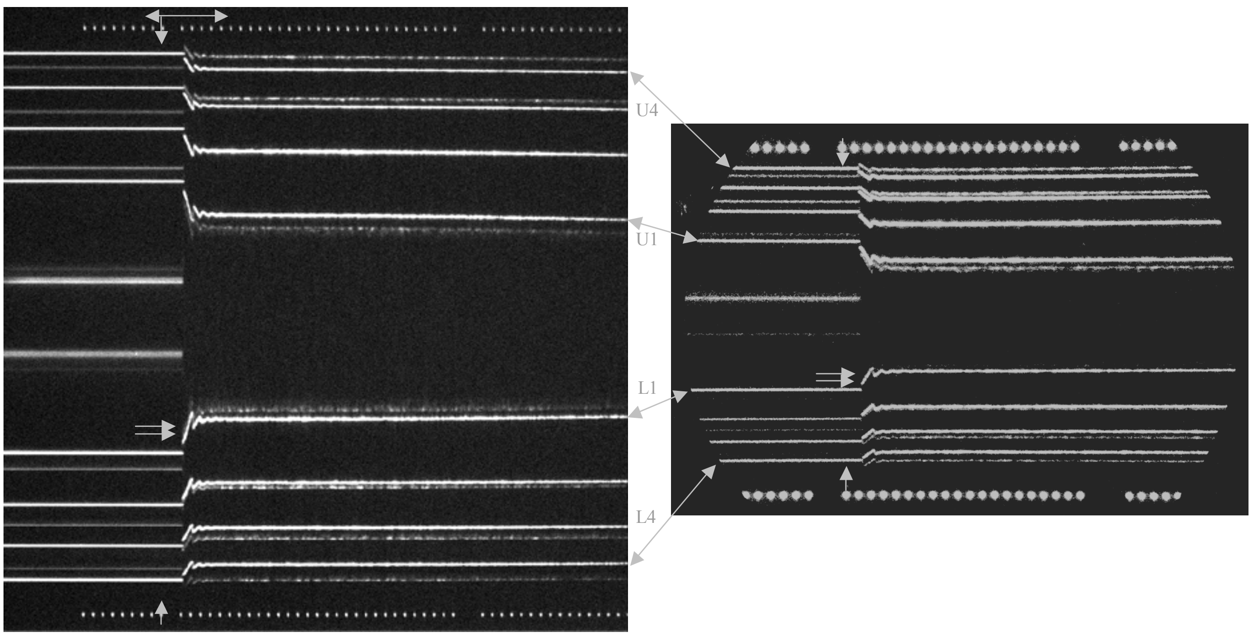

Figure 4. CCD captured image of the galvanometer deflected streak camera. The total record length is 32μs.

Figure 5. Intensity-linearized film image acquired by the electronic streak camera. The total record length is 22μs.

4.2. Spatial Resolution

Fringe trance clarity can be quantitatively examined by plotting the intensity profile variation along the spatial axis. Intensity scan is performed for both images at the temporal location prior to jump-off where the signal strength is higher and stable. The instance is indicated by the vertical arrow pair in Figures 4 and 5. Figures 6 and 7 show the intensity profile plot for the galvanometer and the electronic streak camera result, respectively. The intensity data base is 5-column average for both plots. Those fringe peaks of higher intensity are the primary set and the lower intensity are the secondary set. The first and the last peaks in Figure 6 are the fiducial marks, whereas the first peak of saturated intensity in Figure 7 is the fiducial mark. Figures 6 and 7 are arranged horizontally such that all corresponding fringe peaks are roughly aligned vertically. Visually, Figure 6 shows a much shaper peak with narrower width for all the fringe traces.

The optical spatial resolution of Fabry-Perot fringes can be best quantified in finesses, a dimensionless parameter. Finesse of the n-th order peak is defined as $F_n = (D_{n+1}^2 - D_n^2)/(4 \times D_n \times \Delta_n)$ where D_n is the spatial separation between the pair of n-th order peaks and Δ_n the Full-Width-Half-Max of the upper or the lower n-th order peak. Accordingly, the finesse for all the primary fringes are measured from Figures 6 and 7 and plotted in Figures 8. The x-axis in Figure 8 are labels for the fringes, with U(n) and L(n) for the upper and the lower n-th order peak, respectively. These labels are also shown on the top of Figure 6 to identify its respective fringe. Since both signal channels share the same etalon, the measured difference in finesse then becomes a quantified spatial resolution comparison between the two streak cameras. Figure 8 shows a prevailing higher finesse for the galvanometer camera result except for the fringe U0 of which the electronic camera signal is noisy and weak as evident in Figure 5. This profoundly better finesse of galvanometer camera result means that it does function with a superior spatial resolution.

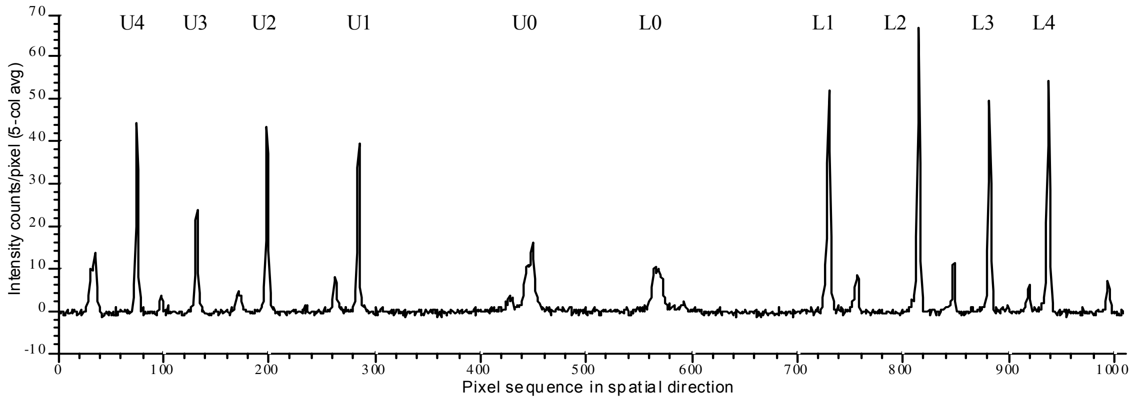

Figure 6. Intensity profile along the vertical spatial axis before jump-off of the galvanometer streak camera record in Figure 4.

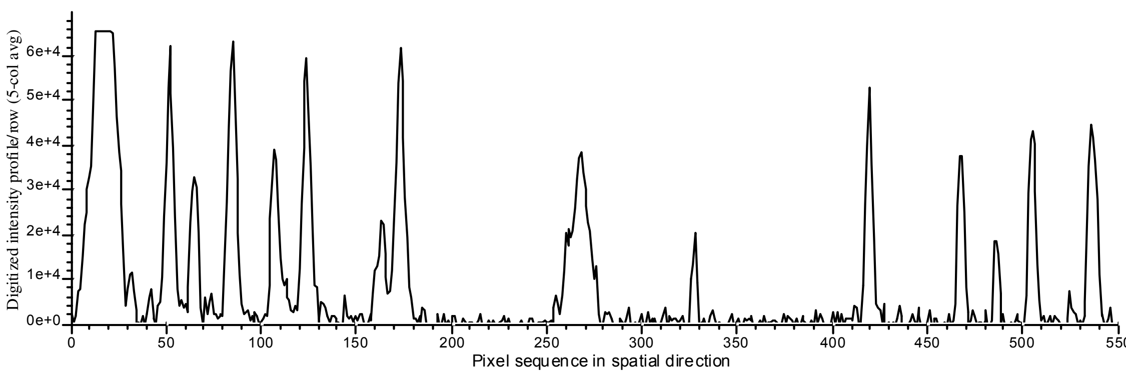

Figure 7. Intensity profile along the vertical spatial axis before jump-off of the electronic streak camera record in Figure 5.

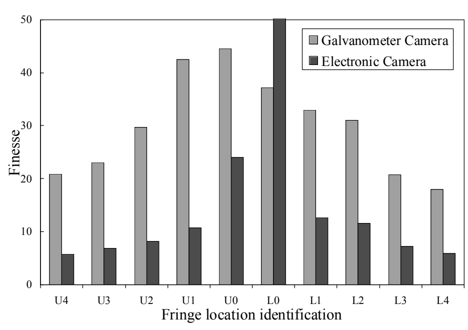

Figure 8. Finesse measurement results of the galvanometer and electronic streak cameras.

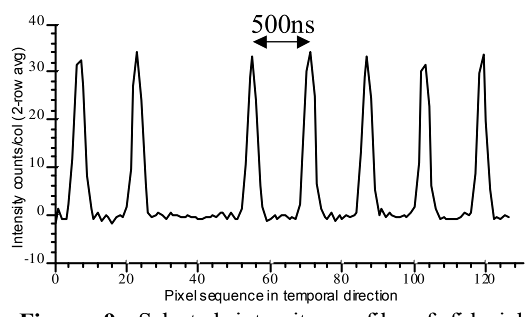

Figure 9. Selected intensity profile of fiducial timing mark registration along the temporal axis.

4.3. Fiducial Timing Registration

The fiducial timing mark registration is relevant especially to temporal imaging performance of the camera. Since the fiducial marks on the electronic camera image are mostly saturated, no analysis is done there. For the galvanometer camera, a portion of the fiducial marks intensity profile covering those eight marks indicated in the upper edge of Figure 4 is shown in Figure 9. Analysis on the complete train of fiducial marks yields an average pixel timing coverage of

31.24ns/pixel. It also shows a timing interval variation of ±0.2 pixel/interval, or ±6ns over 500ns. Most of this variation is due to the digital depth-aliasing or mismatch between pixel center and signal peaking position. An averaging of over sequential 5-interval to reduce the mismatch error, the interval variation becomes ±0.03 pixel/interval or ±1ns over 500ns. The all-optical imaging fidelity and the large inertia deflection of the galvanometer streak camera give rise to the high timing accuracy and constancy as evident by the precise fiducial registration.

4.4. Samples of Temporal Profile Variation

To further assessing the temporal performance, two samples of temporal profile following the jump-off of the first lower order fringe are evaluated at locations as pointed by the two arrows on Figures 4 and 5. Scan along the lower arrow direction gives the one-peak profile shown in Figure 10, whereas along the upper arrow gives the 2-peak profile in Figure 11. Note that these temporal profile plots are not an absolute measure of temporal resolution because the fringes are not vertical traces. Rather, the profile measures a convoluted result of temporal and spatial resolutions. The horizontal pixel timing scales are different for the two images. It is 24.43ns/pixel on average for the digitized electronic streak image and 31.24ns/pixel for the CCD image. The measured FWHMs in time are also shown in the figures. The separation between the two peaks is nearly the same at 310ns on each of the two plots in Figure 11. However, the FWHMs for those on the left of Figure 10 and Figure 11 are substantially narrower and thus demonstrate a superior temporal resolution for the galvanometer camera result.

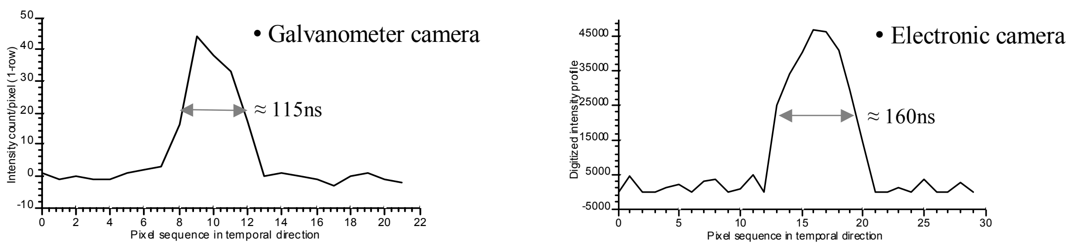

Figure 10. Temporal intensity profile of the first lower order fringe after jump-off along the lower arrow in Figures 4 and 5.

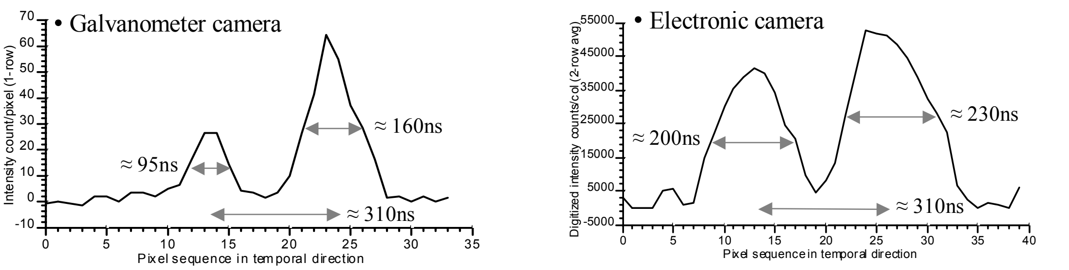

Figure 11. Temporal intensity profile of the first lower order fringe after jump-off along the upper arrow in Figures 4 and 5.

5. CONCLUDING REMARKS

The all-optical deflected streak camera is inherently far superior in imaging performance. We have utilized successfully the galvanometer deflector for the development and design of a compact high-performance camera for fielding application. Results of dual camera side-by-side testing have demonstrated an overall better streak imaging in all key performance parameters reported here for the galvanometer camera than that performed by the electronic camera. Further effort is to develop faster speed capability and expand functional versatilities for this new type of streak camera.

REFERENCES

1. Ching C. Lai, "A new tubeless nanosecond streak camera based on optical deflection and direct CCD image," in *20th International Congress on High-Speed Photography and Photonics*, J. M. Dewey, ed., *Proc. SPIE* **1801,** pp. 454-469, 1992.
2. David Goosman, George Avara, Lloyd Steinmetz, Ching Lai, and Stephen Perry, "Manybeam velocimeter for fast surfaces," in *22nd International Congress on High-Speed Photography and Photonics,* D. L. Paisley, ed., *Proc. SPIE* **2869,** pp. 1070-1079, 1996